AN INVESTIGATION OF
DISTORTION IN CLASS B AUDIO AMPLIFIERS

by

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AUDIO AMPLIFIERS

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An investigation carried out under the
direction of Dr. H.J~~V~~. MacLeod

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of Science. This Thesis represents about
one-half of the total work done toward this degree.

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DISTORTION IN CLASS 'B' AUDIO AMPLIFIERS

INTRODUCTION

With the increasing public demand for high quality broadcasting, the subject of distortion in transmitters has become an important one, and much research is being done along this line at the present time. A number of careful investigations have been made in an effort to determine the amount of distortion of one kind and another that the human ear is capable of detecting. A still further investigation[*] has been carried on recently under the direction of Stuart Ballantine, in which efforts have been made to determine an acceptable and economically realizable standard of performance for high quality broadcast systems. Current Radio literature shows that manufacturers are making every effort to design transmitters that meet such requirements, while operators of stations equipped with older transmitters are attempting to make the necessary improvements, as far as possible, themselves.

A perfect broadcast system would faithfully reproduce the input and add no extraneous sounds. Unfaithful reproduction of the input occurs in three forms.

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[*] See Stuart Ballantine, High Quality Radio Broadcast Transmission and Reception, Proc.I.R.E., Vol. 22, P.564.

1. The ratio of input to output amplitude may not be independent of frequency.* This is known as frequency distortion and is one of the most important forms of distortion occuring in sound transmission. It was not, however, considered in this work as it is in no way peculiar to class B audio-frequency amplifiers.

2. The phase relations of components of various frequencies may be altered. This form of distortion is known as phase distortion and is unimportant in the transmission of sound.** Therefore this also was neglected in this work.

3. The ratio of output to input amplitude may not be independent of amplitude. This is known as amplitude distortion and is a very serious form of distortion occuring in class B audio-frequency ~~and~~ amplifiers. It was therefore considered in this investigation. An actual input-output curve for CKUA was run in May, 1935, and is shown in Graph I. In this case amplitude distortion begins with 50 per cent modulation and becomes quite serious for 100 per cent. Oscillographic records show that such non-linearity is due to a flattening of the output wave.

The addition of extraneous noises is also a serious form of distortion in class B audio-frequency amplifiers. The noises occur in the form of harmonics

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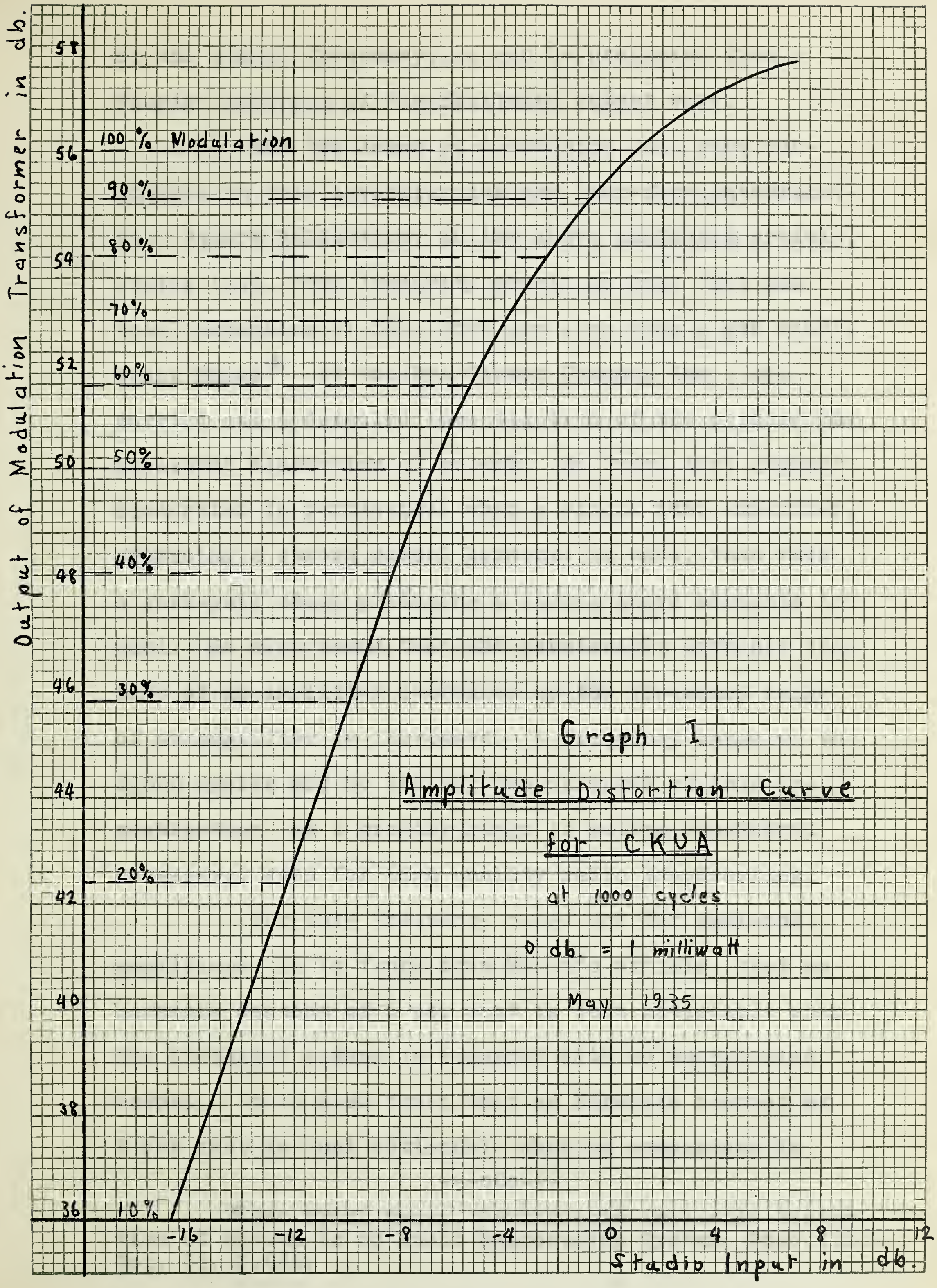
*See McIllwain and Brainerd, High Frequency Alternating currents, P.6.

**See Bath. van der Pol, Proc.I.R.E., vol.18,P.221.



Graph I

Amplitude Distortion Curve

for CKUA

at 1000 cycles

0 db. = 1 milliwatt

May 1935

of the signal frequency, as can be predicted from a Fourier analysis of the flattened output wave.

The two forms of distrotion that were considered in this investigation are therefore interrelated. Stuart Ballantine, in the above mentioned article, states that, "The linearity should be such that the total harmonics at full load are less than 5 per cent". Frank Massa* of the RCA Victor Company Inc., has carried out a detailed investigation of the permissible amplitude distortion of speech. He found that greater distortion is permissible when a single tube amplifier, producing a strong second harmonic is used, than when a push-pull stage producing a strong third harmonic is used. He also found that the permissible harmonic content of an amplifier decreases as the frequency range of an amplifier is increased. A frequency range up to 8,000 cycles may be set for the purposes of this investigation, as a greater range is seldom considered necessary, even for high quality radio braodcasting.

For this frequency range and for push-pull amplifiers, it is found from Massa's article, that an harmonic content of 5 per cent is just noticeable when the distorted output is compared with an undistorted output. It is also found that an harmonic content of 7 per cent is just noticeable when no comparison is

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*See Frank Massa, Permissible Amplitude Distortion of Speech in an Audio Reproducing System, Proc.I.R.E., Vol. 21, P.682.

made. Thus it is seen that the 5 per cent maximum permissible harmonic content set by Ballantine is conservative. Interesting articles[*] are still appearing, treating this matter in still greater detail. In the United States the sum of all audio harmonics present in a modulated radiation is limited to 10 per cent by the Federal Radio Commission.

Because of the interrelation of Amplitude distortion and harmonic content in radio broadcast systems, it is possible to take care of both forms of distortion with this one requirement, but it must be applied to the entire broadcast system.

In modern design of transmitters class B modulators have become very popular because of the large amount of audio-frequency power that can be generated at a reasonable cost, making high level modulation practicable. In operation, the grids of class B modulators are driven decidedly positive on the signal peaks for the larger outputs. In such transmitters the modulators are by far the most important source of amplitude distortion. Other sources may therefore be neglected.

The purpose of this investigation was to determine the causes of amplitude distortion in class B audio-frequency amplifiers, and also the rules to be followed in design and operation to make it a minimum.

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[*] See J. A. Hutcheson, the High Quality Problem, Communication and Broadcast Engineering, July, 1935.

This was done as follows:

1. Different loads on the output transformer of a class B audio-frequency amplifier were tried. For each load, curves of output, efficiency and harmonic content were plotted on an input base. The effect on each, due to the difference in load, was noted.

2. Various resistances were added to the plate supply of the class B amplifier; curves of output and harmonic content were plotted on an input base for each resistance; and differences were noted.

3. Various resistances were added to the grid circuit of the class B amplifier. The same curves as in part 2 were plotted and the differences noted.

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DESCRIPTION OF APPARATUS

A diagram of the amplifier actually used is shown in figure I. It is an audio-frequency system designed by The Hammond Manufacturing Company of Guelph, Ontario, and is capable of modulating a 100 watt carrier 100 per cent when operated with 500 volts on the plates of the output tubes. The tubes used in the modulation or output stage were type 210 with metal plates, and they were operated with 425 volts on the plates, their maximum rating. The maximum rated plate voltage for type 210 tubes with graphite plates is 600 volts and these would have met the Hammond specifications.

The grid bias required to operate the output stage as a class B amplifier was determined as - 45 volts, from the curves of Graph II in the manner described by B. J. Thompson.* These curves are the actual characteristics of the two tubes used and they are seen to be well matched.

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* See B. J. Thompson, Graphical Determination of Performance of Push-Pull Audio Amplifiers, Proc.I.R.E., Vol. 21, P.591.

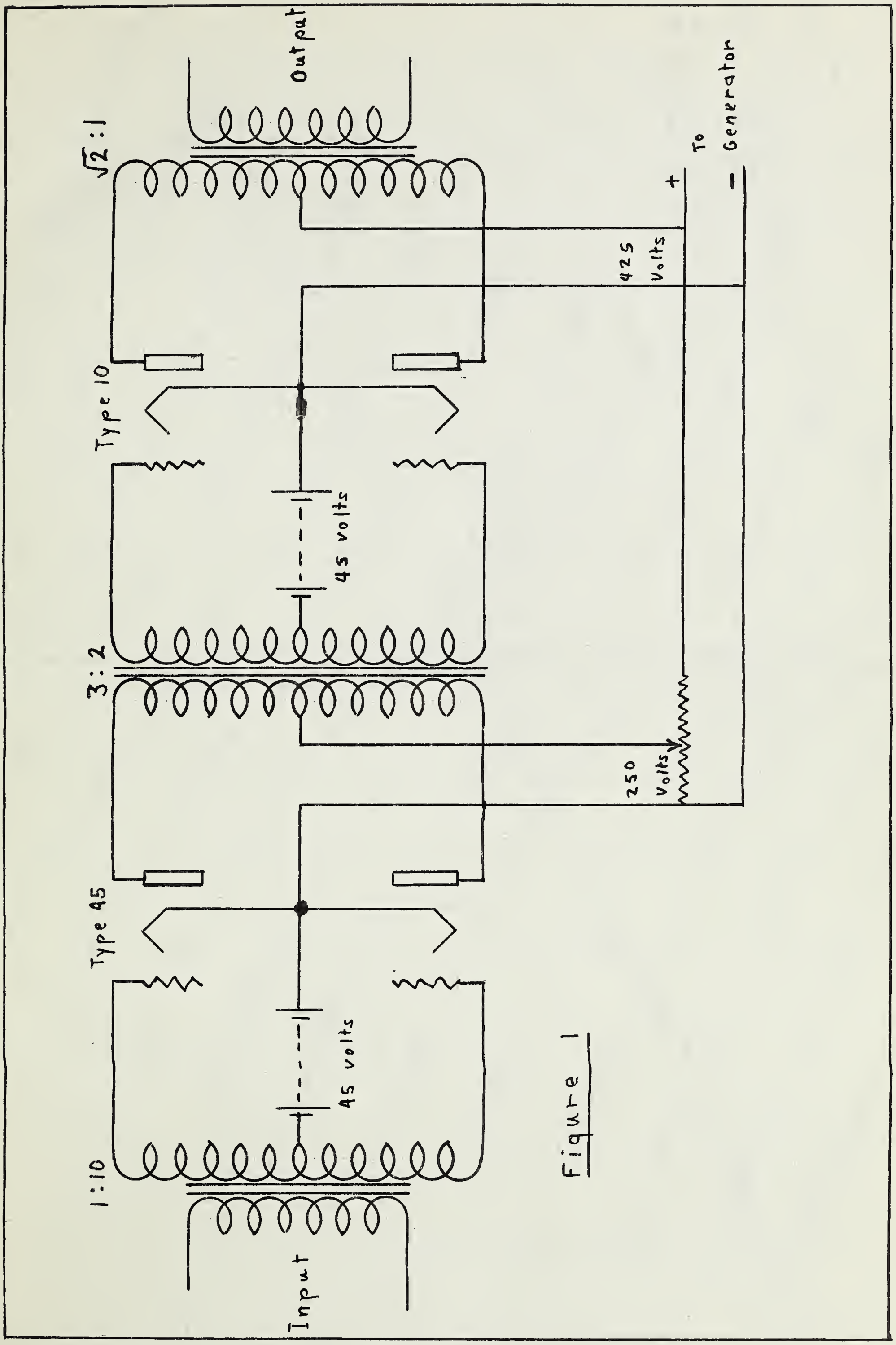
Output
$\sqrt{2}:1$
To
+
− Generator
425 Volts
Type 10
45 volts
3 : 2
250 Volts
Type 45
45 volts
1:10
Input

Figure 1

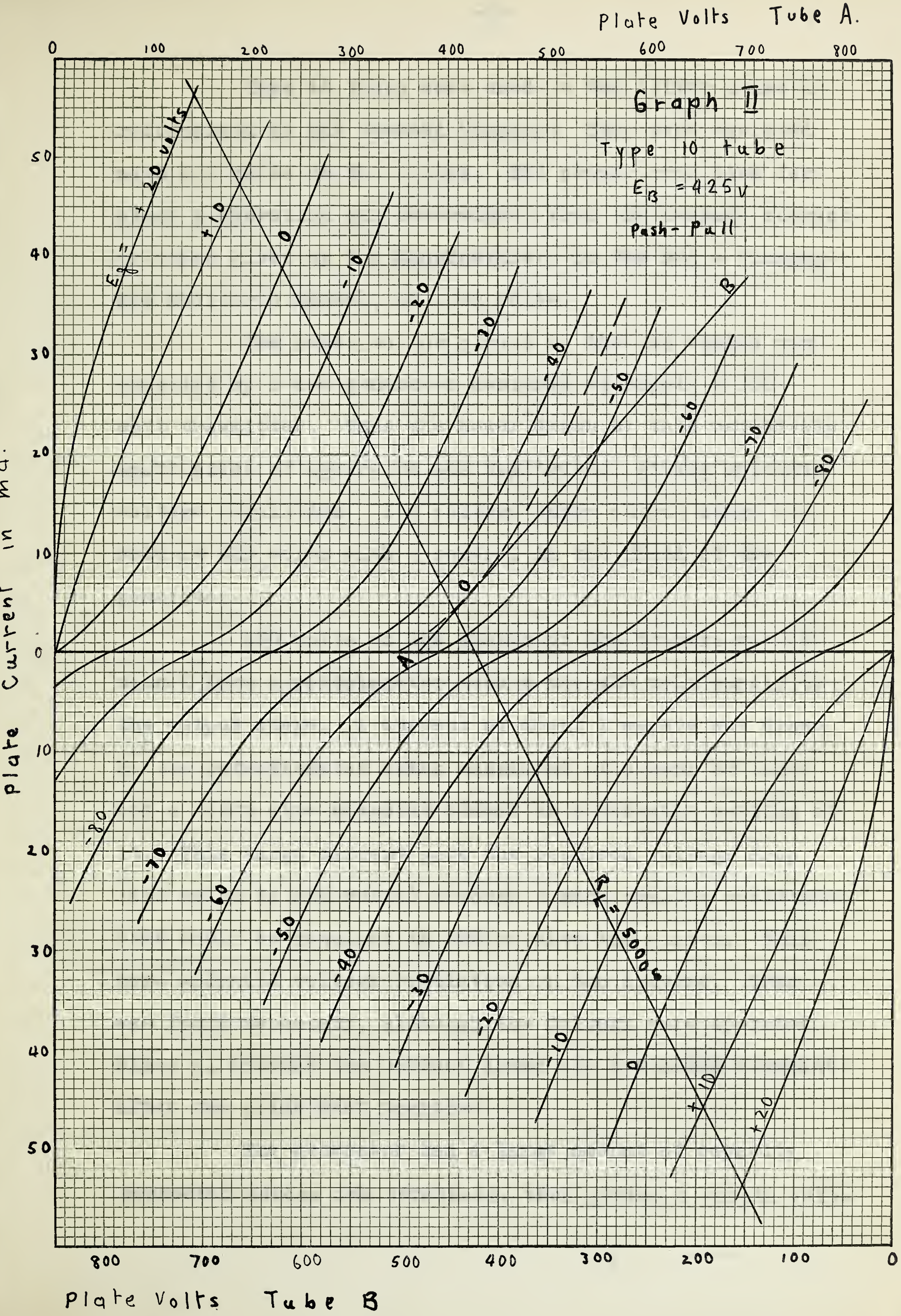
Plate Volts Tube A.
0
100
200
300
400
500
600
700
800
Graph II
Type 10 tube
E_B = 425v
Push-Pull
Eg = +20 volts
+10
0
-10
-20
-30
-40
-50
-60
-70
-80
B
A
0
R_L = 5000 Ω
Plate Current in ma.
50
40
30
20
10
0
10
20
30
40
50
800
700
600
500
400
300
200
100
0
Plate Volts Tube B

Type 45 tubes were used in the driver stage as recommended by the Hammond Company. They were operated with 250 volts on the plates. The proper grid bias for class A operation was determined, from the average characteristics given by the Manufacturers in the RCA - Cunningham Radiotron Manual, as - 45 volts.

The power to the plates of the two stages was supplied by a d-c generator designed to supply a 500 watt trasmitter. Thus the power drawn by this relatively small piece of apparatus was negligible, giving splendid voltage regulation. The voltage onthe output stage was held at 425 volts with a control in the field of the generator.

250 volts on the plates of the drivers was obtained from a potentiometer across the 425 volt supply to the output stage. A current of about 1 ampere was drawn by the potentiometer which consisted of a bank of lamps and a slide wire rheostat placed in a suitable portion of it. This large current gave the required voltage drop (425 volts to 250 volts) through a much smaller resistance than would be required in series with the plates. This gave splendid voltage regulation on the drivers. This was found necessary, although the drivers were operated class A, because the current drawn was not quite constant after the grids went positive.

The generator had a large amount of capacity connected across its terminals, thus giving a smooth volt-

age over the audio cycle.

The transformer used in each position was that recommended by the Hammond Manufacturing Company, and was in each case as follows:

Input transformer - Hammond, type 426, line to push-pull grids.

Interstage transformer - Hammond, type 2150, push-pull plates to push-pull grids.

Output transformer - Hammond, type 2155, push-pull plates to load. (8,000 ohms, plate to plate, to 4,000 or 6,000 ohms load).

The transformation ratios are given in figure I, and are in each case, the ratio of the total primary winding to the total secondary winding.

It was decided that all measurements should be made at 1000 cycles, as this is about the average audio-frequency that a Radio transmitter is required to handle. The source used was a 1000 cycle, vacuum tube oscillator. The output was analysed with an harmonic analyser, and the harmonic content was found to be about 0.6 per cent. This was considered satisfactory.

The oscillator was coupled to the amplifier through a pick-up coil and potentiometer, as shown in figure ~~2~~3. As the resistance of the potentiometer was small relative to the input resistance of the first stage of the amplifier, the load on the oscillator remained nearly constant for all settings of the potentiometer. This guaranteed a reasonably constant frequency.

A pure resistance load, including the harmonic analyser, was connected across the output transformer. The harmonic analyser used is described in the appendix, It was a type which measures the combined effect of all harmonics as a per cent of the total output. This was satisfactory, as in high quality transmission of sound, it is the total harmonic content that the engineer is interested in. The analyser was capable of reading harmonic contents of 0.5 per cent and upwards with an error of about 3 per cent.

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NORMAL OPERATION OF THE AMPLIFIER

The amplifer was set up for normal operation as shown in figure 3. It was driven by the 1000 cycle oscillator, through the potentiometer as explained above. The load connected across the secondary of the output transformer was 4,000 ohms, as recommended by the Hammond Manufacturing Company. This gave a load of 2,000 ohms on the plate of each tube in the output stage.

The input, measured at the potentiometer, was increased through 18 steps from 0 to 7.5 volts. For each step, the output current was read on a milliammeter, and the harmonic content of the output was obtained from the harmonic analyser. The curves of output current and harmonic content were then plotted on an input base, as shown in Graph III. Another curve, of output voltage from one half of the interstage transformer with no load on it, was run and also plotted in Graph III. This curve was run with a cathode-ray oscillograph because the input impedance of this instrument is very large. The points obtained do not give as smooth a curve as might be expected, because it is difficult to read this instrument accurately.

Curves of output against input in audio-frequency work are usually plotted in decibels. It was found impossible to follow this rule in this case. The input impedance of the amplifier was non-linear as the grids of the input stage went positive in the range covered. This means that the power drawn from the oscillator by the

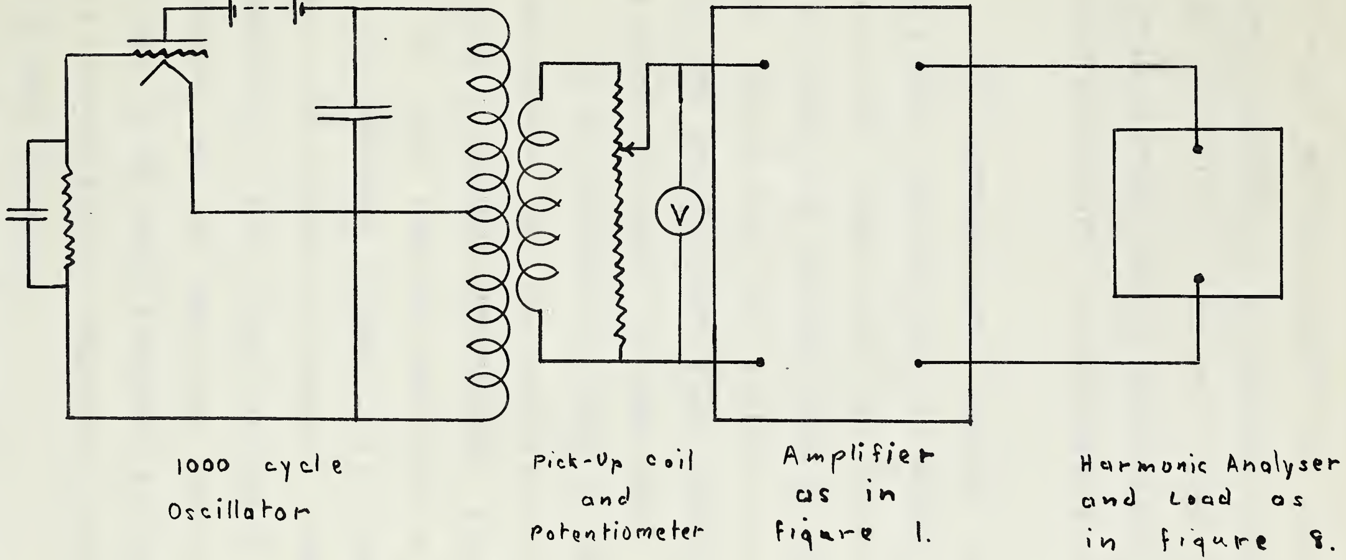

1000 cycle
Oscillator
Pick-Up coil
and
potentiometer
V
Amplifier
as in
figure 1.
Harmonic Analyser
and Load as
in figure 8.

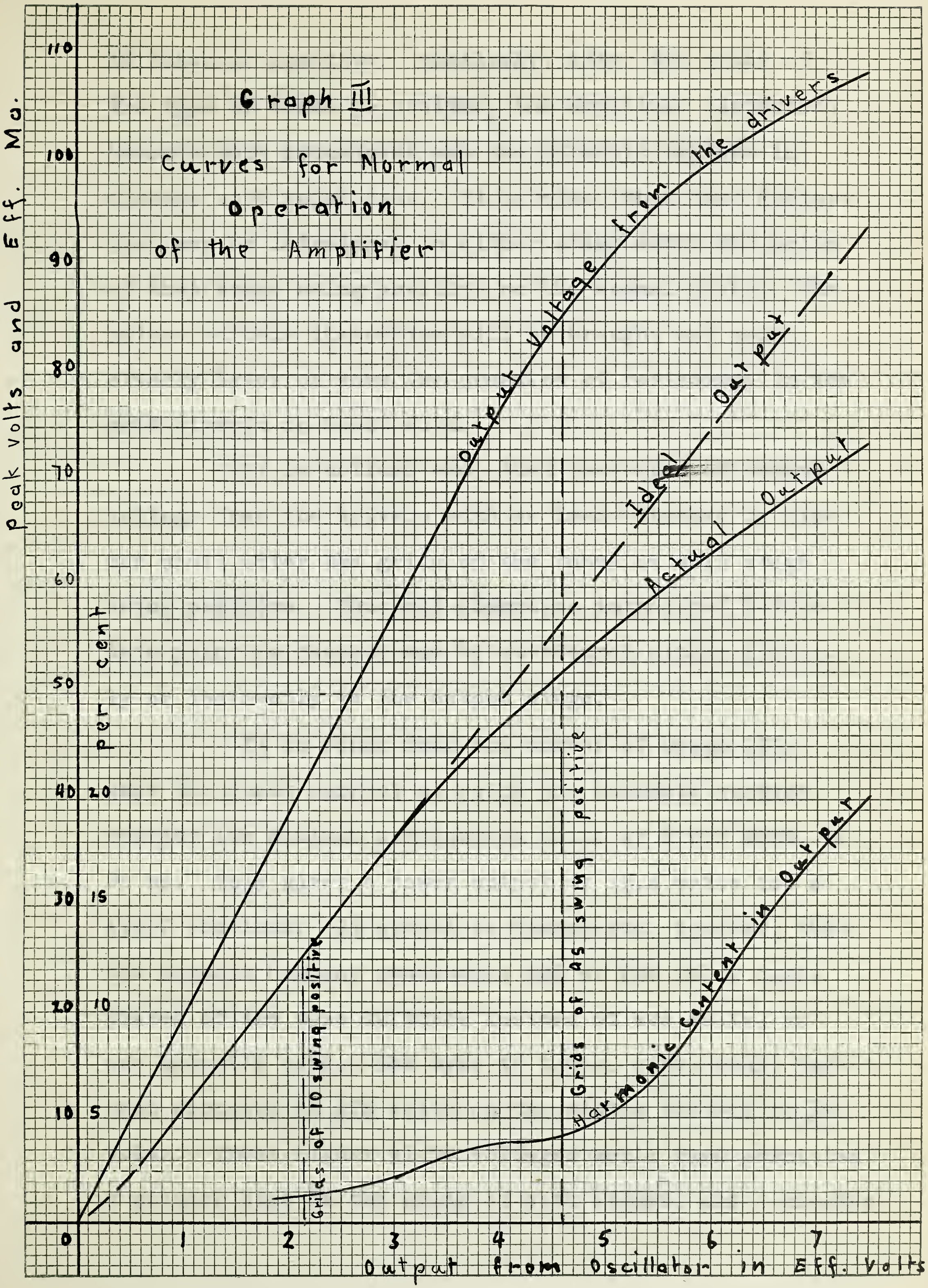
Figure 3

amplifier was not a linear function of the applied voltage. Yet the output of the amplifier for linear operation, must be a linear function of the applied voltage. Therefore, since the decibel is a measure of power level, curves plotted in decibels would not be satisfactory. Because of this the output was plotted in milliamperes on an input voltage base.

Milliammeters were inserted in the grid circuits of both stages, and the inputs at which the grids went positive on the signal peaks were found by noting the points at which grid current began to flow. It was found that the type 45 tubes went positive at an input of 4.6 volts and the type 10 tubes at an input of 2.15 volts. These points were marked on Graph III.

As the harmonic contents of the larger outputs were much greater than the permissible value, the range covered was considered wide enough. It must be remembered that the input from the oscillator to the amplifer had 0.6 per cent harmonic content in it to start with, and that the 5 per cent permissible harmonic content set by Ballantine is conservative. Then, since sources of amplitude distortion other than the modulation stage are relatively unimportant in the usual broadcast system, 5 per cent harmonic content will be considered permissible in the output of this amplifier.

It is at once noticed from Graph III that amplitude distortion starts and harmonic content starts to increase, almost immediately after the grids of the type


Graph III

Curves for Normal Operation of the Amplifier

10 tubes go positive. Similarly, after the grids of the type 45 tubes go positive, the amplitude distortion becomes more pronounced and the harmonic content increases at a rapid rate. It is clear then that distortion may be introduced in either stage after the grids of that stage swing positive on the signal peaks. The nature of this distortion will be brought out more clearly later on when the question of resistance in the grid circuit is dealt with.

It is noticed too, that the curve of output voltage from the drivers with no load attached is linear until after the grids of the tubes in this stage swing positive. Thus all distortion introduced before this point is reached may be attributed either directly or indirectly to the output stage.

It is found from the curves of Graph III, that the output current at which the harmonic content reaches its maximum permissible value of 5 per cent, is 56 ma. This gives a power output of 12.5 watts for a 4,000 ohm load. It should be remembered, however, that the Hammond Company recommends 500 or 600 volts onthe plates of the type 10 tubes instead of 425 volts, as was actually used. The type 45 tubes, also, could have been operated at 275 volts on the plates instead of 250 volts. These higher plate voltages would have permitted a greater bias on the grids of both stages, and a greater

input before the grids would go positive on the peaks. Thus the permissible power output would have been considerably increased, since it varies approximately as the square of the signal voltage.

Well designed drivers for class B modulators are operated class A and the grids do not go positive, except perhaps a little for 100 per cent modulation. In some stations, however, the operators may find that the grids of the drivers are swinging quite positive on the peaks for the larger outputs, as shown in Graph III. In such cases it is probably better to operate the driver class AB or even class B and thus keep the grids negative throughout the cycle. There will then be a small increase in harmonic content for the smaller outputs, where it can usually be tolerated; and a considerable decrease in harmonic content for the larger outputs, where decrease is needed. The plate current to the drivers is usually drawn through a voltage dropping resistor, and such a resistor cannot be used when the drivers are changed from class A to class AB or class B operation, because the plate current is no longer steady.

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OPTIMUM LOAD

Let a pure resistance load R_l be connected across the secondary of the output transformer of a class B push-pull amplifier, as shown in figure 4. Since the tubes are biased to cut-off, only one tube operates at a time, and the half of the transformer connected to the other tube may be thought of as open. Then if the turn ratio of the total primary to the secondary is N, the load resistance is transferred into the plate circuit of the operating tube as $(\frac{n}{2})^2 R_l$.

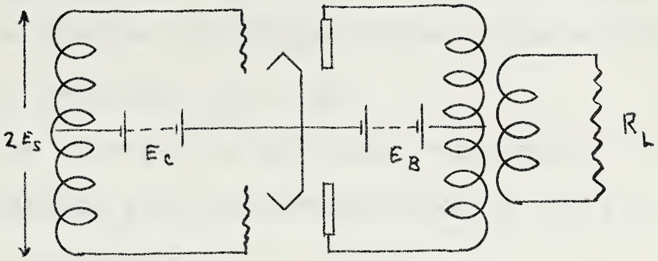

Figure 4

The optimum load on a class B push-pull amplifier is the load giving maximum power output for a signal~~l~~ of fixed amplitude. It may be found by modifying Terman's derivation* of optimum load on a single tube operating class B.

Let E_s be the amplitude of the signal voltage
E_B be the voltage of the plate supply
E_c be the grid bias voltage

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*See F.E. Terman, Radio Engineering, P.212.

μ be the amplification factor of the tube

I_m be the crest value of the plate current impulses

I_{ac} be the amplitude of the signal frequency component contained in the plate current impulses

r be the d-c resistance of the plate circuit

α be the ratio I_{ac} / I_m.

Then r may be taken as the plate resistance of a single tube, assuming other d-c resistances in the plate circuit are negligible.

The chief difference between this analysis for a push-pull class B amplifier and Terman's analysis for a single tube class B amplifier, is that $\alpha = 1$ for the push-pull amplifier since one tube comes into operation as the other goes out, while $\alpha = 0.5$ for the single tube amplifier. Therefore:

$$I_{ac} = I_{am} \tag{1}$$

Since the tubes are biased to cut-off

$$E_b = \mu E_c$$

and the plate supply and grid bias voltages balance each other out. Therefore

$$I_m = \frac{\mu E_s - I_{ac} \left(\frac{n}{2}\right)^2 R_L}{r}$$

Combining with equation (1)

$$I_{ac} = \frac{\mu E_s}{r + \left(\frac{n}{2}\right)^2 R_L} \tag{2}$$

The power output to the load

$$= \frac{(\mu E_s)^2}{2} \frac{(\frac{n}{2})^2 R_L}{\left\{r + (\frac{n}{2})^2 R_L\right\}^2} \qquad (3)$$

It can now be shown by differentiating equation (3) with respect to $(\frac{n}{2})^2 R_L$ and equating to zero, that the maximum power output for a given input is obtained when

$$(\frac{n}{2})^2 R_L = r.$$

Then for maximum power output each tube should operate into a load equal to its plate resistance. This can be compared with class A operation of a single tube where current flows throughout the cycle.

In the above analysis no allowance was made for variation in plate resistance. This is actually far from constant, especially in the neighborhood of cut-off where it rapidly increases and finally becomes infinite. When the bias is adjusted to cut-off for the composite characteristics (See Graph II), current is actually flowing in each tube and the actual operating point for a single tube is on the curved portion of a single tube characteristic. Thompson* shows that the optimum load is actually equal to one-half the plate resistance of a single tube at this operating point. This load resistance is somewhat less than the plate resistance given in Vacuum Tube Manuals. Thompson further shows, that when this optimum load is used, "each tube operates into an effective load

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* See B. J. Thompson, Graphical Determination of the Performance of Push-Pull Audio Amplifiers, Proc.I.R.E., April 1933, P.594.

resistance equal to its own internal resistance at every point throughout the cycle".

There are two points that should be noted here in passing.

1. The optimum load is not critical. Referring again to Thompson's article (figure 4) it is seen that decreasing the load from its optimum value of 4,000 ohms to 2,000 ohms, or increasing it to 7,000 ohms, only decreases the power output of the amplifier about 8 per cent. This gives the designer ~~a~~ considerable range in ~~to~~ choos~~e~~ing a value ~~from~~.

2. While the optimum load gives the maximum power output for a given signal input, the plate efficiency of the amplifier is low and increases rapidly as the load resistance is increased. This point is only of importance when considerable amounts of power are involved.

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DISTORTION AT DIFFERENT LOADS

The optimum load on a class B audio-frequency amplifier was determined in the preceding section, but this is not necessarily the best load to use when the harmonic content is to be held below a certain fixed amount. In fact optimum load may not even give maximum output for a given signal input after amplitude distortion sets in.

The optimum load on two type 10 tubes operating class B may be found from Graph II. It is the slope of the tangent AOB at the operating point O of a single tube, and is approximately 4,000 ohms. In Graphs IV and V the results of tests runfor a 2,000 ohm load and a 5,000 ohm load are shown. In both cases the operating conditions were normal.

Curves of power output and efficiency are plotted in Graph IV for both loads. The power output curves are plotted in watts on a voltage input base and are not straight lines, since, in the region of linear operation, output in watts varies as the square of the input in volts. These curves give an excellent comparison of power output for the two loads, for given voltage inputs; but cannot be used to study distortion. Therefore, curves of output in milliamperes have also been plotted on a voltage base in Graph V, along with curves of harmonic content.

The curves of Graph VI are simply the I_p - E_p characteristics of a type 10 tube. It was found necessary to extend these curves well into the positive grid region for this work. The usual static method of obtaining vacuum tube characteristics cannot be used in this region, since large plate voltages draw excessive plate currents when the grid is positive, sometimes damaging the tube and at least distorting the results from those obtained in practice when the grid swings positive for a small part of each cycle.

A condenser - discharge - oscillographic Method of obtaining these characteristics has been proposed by Mouromtseff and Kozanowski.* A condenser is charged to the desired positive potential and then suddenly discharged through a resistance from grid to filament. Thus the desired potential is instantaneously applied to the grid and the peak of the rush of the current in the plate circuit is caught on an oscillograph. This method has the following disadvantages.

1. It is difficult to read an oscillograph accurately.

2. A non-inductive power supply is required for the plate circuit. The inductance in the choke of a power supply filter, or even in the armature of a generator, tends to smooth out the rush of plate current, and thus the values of current read from the oscillograph are too small.

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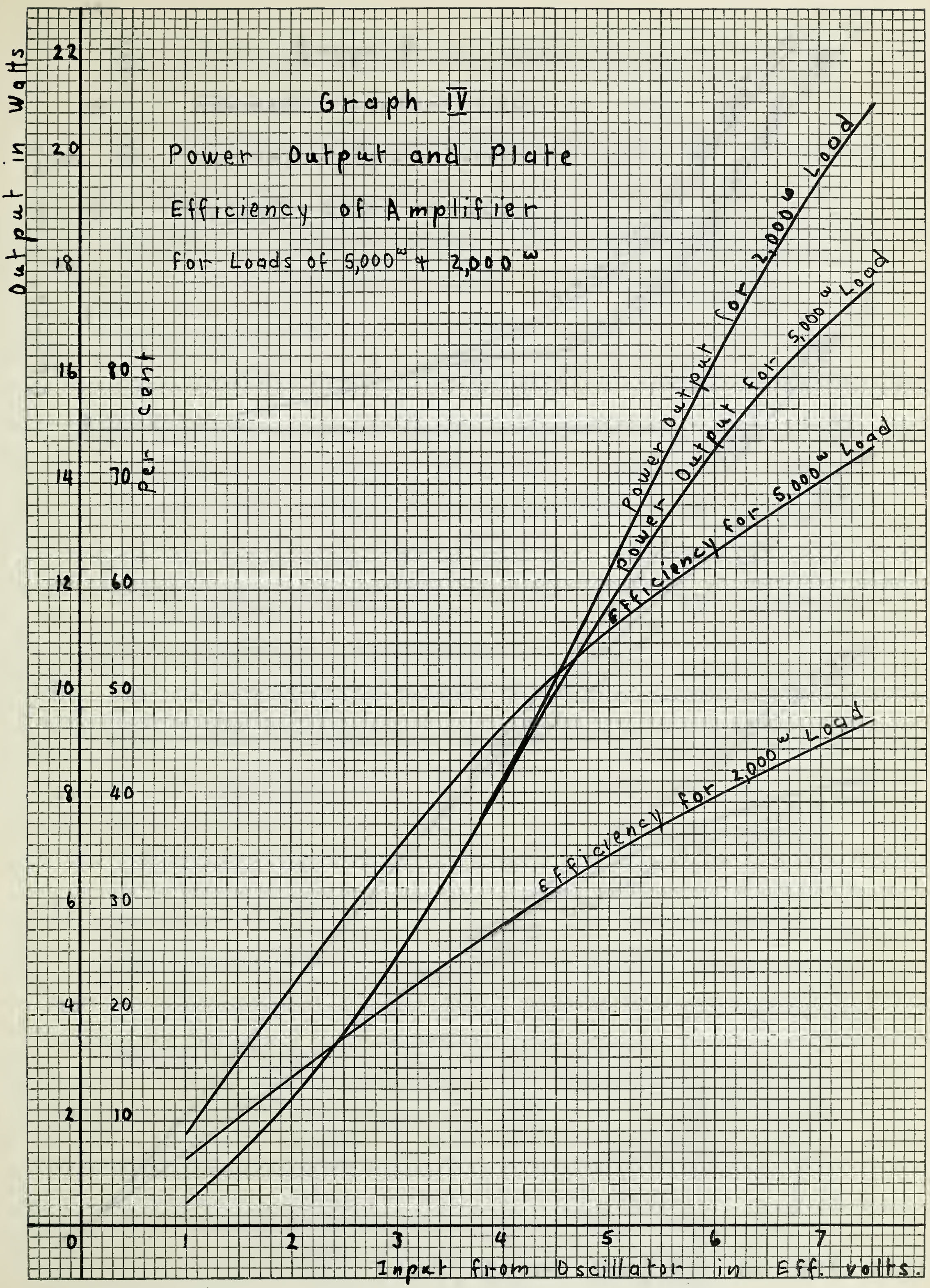
*See H.N. Kozanowski and I.E. Mouromtseff, Vacuum Tube Characteristics in the Positive Grid Region by an oscillographic method, Pro.I.R.E.,vol.21, P.1082.

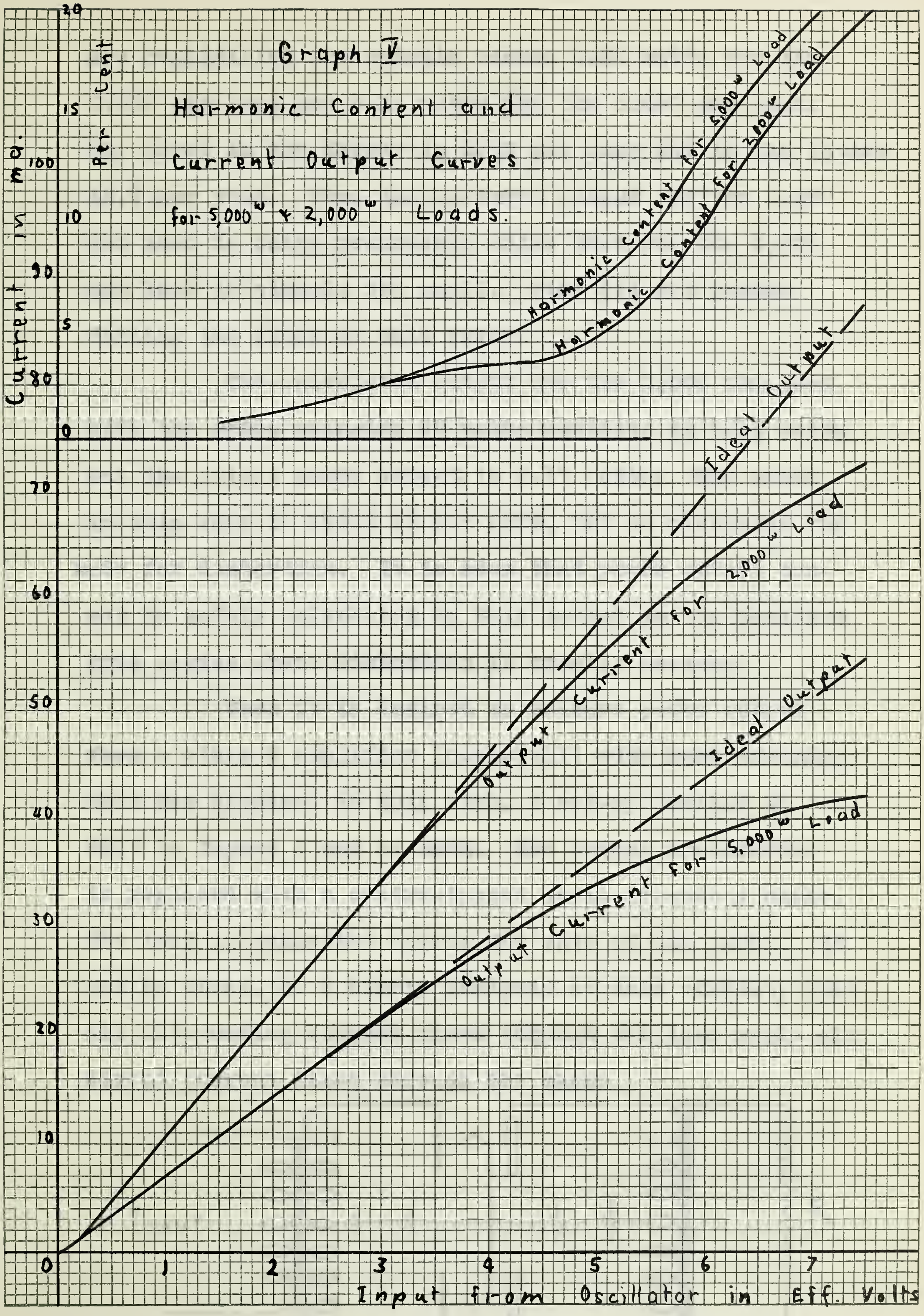
Because of these disadvantages the characteristics in the positive grid region were obtained by the usual static method, but positive potentials were applied to the grid only while readings were being taken.

The composite operating point of the two tubes has been taken from Graph II and marked on Graph VI. Through this point,load lines for 2,000 ohms and 5,000 ohms have been drawn.

Since the 5,000 ohm load is nearer the optimum load of 4,000 ohms than the 2,000 ohm load, the output for the former should be greater than for the latter over the region of linear operation. These outputs may be calculated from Graph VI for a given input, for example, a signal of 45 volts amplitude on the grids of the type 10 tubes. This signal brings the grids to zero on the peak and is still in the linear region. For the 2,000 ohm load we get a peak plate current of 57.5 ma. and a peak plate voltage of 115 volts. This gives a power output of 3.31 watts. Similarly for the 5,000 ohm load the power output is found to be 3.54 watts. The latter is somewhat greater as predicted, but the difference is less than 7 per cent showing again that the optimum load is not critical.

The actual power output is read from graph IV as 3.11 watts in both cases. When a correction is made for power losses in the transformer windings (Iron losses


Graph IV
Power Output and Plate
Efficiency of Amplifier
For Loads of 5,000ω + 2,000ω
Output in Watts
per cent
0
2
4
6
8
10
12
14
16
18
20
22
10
20
30
40
50
60
70
80
1
2
3
4
5
6
7
Input from Oscillator in Eff. volts.
Power Output for 2,000ω Load
Power Output for 5,000ω Load
Efficiency for 5,000ω Load
Efficiency for 2,000ω Load



Graph V

Harmonic Content and Current Output Curves for 5,000w & 2,000w Loads.

are negligible) the outputs become 3.22 watts for the 2,000 ohm load and 3.14 watts for the 5,000 ohm load. The error in the former is 2.80 per cent and in the latter 12.7 per cent. Thus the measured output for the 2,000 ohm load is quite reasonable while that for the 5,000 ohm load is clearly too small. Time did not permit finding the cause of this error.

The calculated output for the 2,000 ohm load with the grids swinging 30 volts positive is 9.14 watts and the actual power output is 8.17 watts. The error in this case is about 12 per cent, but no allowance was made for distortion. It is seen that power output cannot be safely calculated by this method in the positive grid region where distortion is usually serious.

When it is desired to measure power output from a class B amplifier (push-pull) with more accuracy than was obtained in this work, a set-up similar to that in figure 5 may be used. The output transformer is replaced with a centre-tapped audio-frequency choke. The load is connected across the ends of the choke. It can be shown, by a simple analysis of this circuit, that all alternating current flows through the load while all direct current flows through the choke.

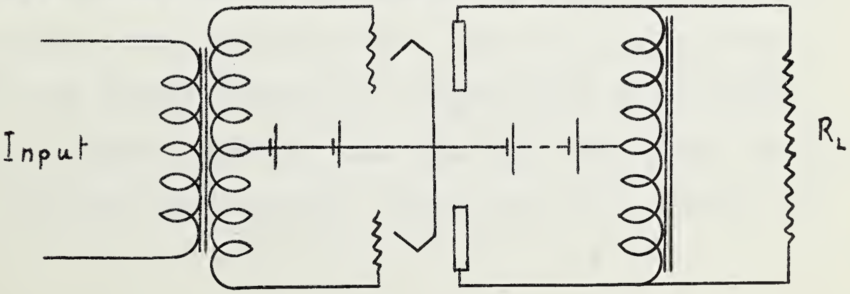
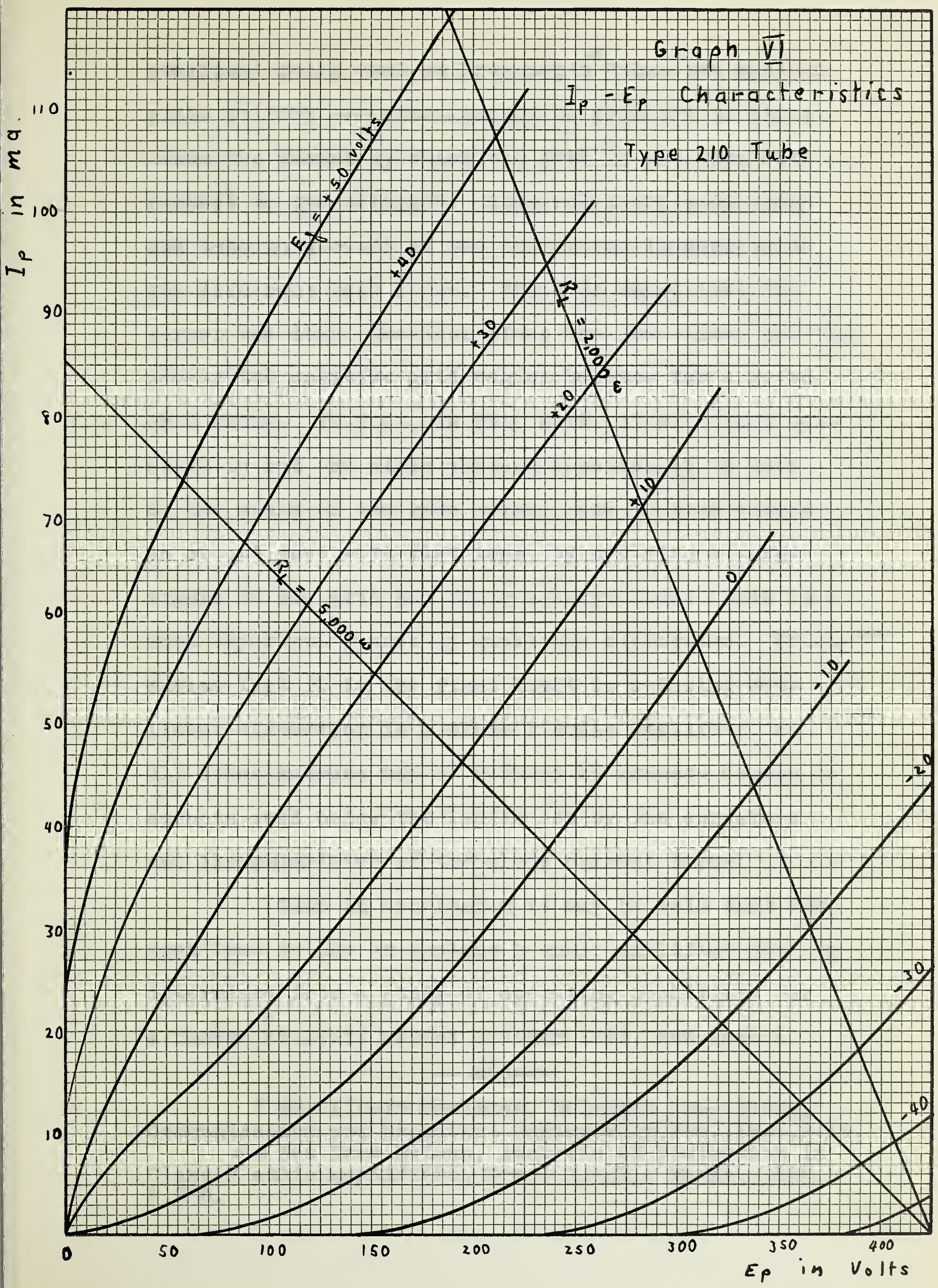


Figure 5.

Thus the losses in the choke add in with the losses in the power supply and the plates, while the entire a-c output is dissipated in the load. In this manner a-c losses in the output transformer are entirely avoided.

Referring again to Graph IV, it is seen that the output for the 2,000 ohm load is much greater than that for the 5,000 ohm load in the region where distortion is pronounced. This is the opposite to what would be expected from a consideration of optimum load. Referring now to Graphs IV and V together, it is seen that when the harmonic content of the output is limited to 5 per cent, the maximum permissible output for the 2,000 ohm load is 12.5 watts while that for the 5,000 ohm load is only 9 watts. Therefore the 2,000 ohm load, which is only one-half the optimum load, gives an output 39 per cent greater than the 5,000 ohm load, which is near the optimum load, without exceeding the permissible harmonic content. This increased output, however, is at a greatly decreased plate efficiency; the efficiency for the 2,000 ohm load being only 35 per cent and that for the 5,000 ohm load being 50 per cent.

The reason for this increased output without undue distortion is readily discovered from the vacuum tube characteristics of Graph VI. It is at once noticed that the characteristics in thepositive grid region tend to crowd together, and the lower the plate voltage the greater the crowding. This leads to a number of


Graph VI
I_p - E_p Characteristics
Type 210 Tube
I_p in ma.
E_p in Volts
E_f = +50 volts
+40
+30
+20
+10
0
-10
-20
-30
-40
R_L = 2,000 ω
R_L = 5,000 ω
110
100
90
80
70
60
50
40
30
20
10
0
50
100
150
200
250
300
350
400

empirical rules such as Preisman's* "that the minimum plate voltage ----------should be from two to three times the amount by which the grid is positive with respect to the cathode". Such rules are very rough and take no account of the difference in conditions for different load lines. Graph VI shows that the larger the load, the less steep the load line, and the poorer the positive grid region becomes for a given grid swing. In fact, in this work, it was found possible to cut the plate voltage practically to zero on the peaks of the grid swings, and to thus obtain an output wave with flat tops, by applying a large signal to the grid and using a large load. This is a most important source of amplitude distortion. McLean** claims that it is the final limit in reducing non-linear distortion in a class B audio amplifier, as all other sources may be reduced by adequate design to amounts well below the limits set by the curvature and irregularities of the plate current curve.

Then in conclusion it may be said that the best load to use on a class B audio amplifier must be determined from a study of operating conditions for a number of loads around optimum load, and from a

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* See Albert Preisman, Balanced Amplifiers, Communication and Broadcast Engineering, Feb., 1936, P.14.

** See True McLean, Analysis of Distortion in Class B audio amplifiers, Proc. I.R.E., March, 1936, P.508.

consideration of the radio-frequency stage to be modulated. A load larger than optimum load will give an output only slightly smaller but at a higher efficiency for a given input. This is clearly brought out by the curves of efficiency shown in Graph IV. The harmonic content, for a given output will in most cases be larger, when the load is greater than optimum.

On the other hand, a load smaller than optimum will have a considerably decreased harmonic content for a given output. The output for a given input will only be slightly decreased, but the efficiency will be decreased considerably. Then the best load for the modulator in a small transmitter, where efficiency is unimportant, is generally less than the optimum load.

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THE CALCULATION OF HARMONIC CONTENT

The general problem of the calculation of the harmonic content in a given wave is of course based upon a Fourier analysis of the wave. Since the determination of Fourier coefficients is tedious, and since harmonic analysis is a problem frequently occurring in the design of radio transmitters, a number of short-cut methods have been devised. These methods are shorter because simplifying assumptions are made at the start and generality is thus lost. Therefore, in applying these short-cut methods, one must be sure that these fundamental assumptions hold for the particular case in hand.

In the following work, the harmonic content for the 2,000 ohm load and an output of 12.5 watts is calculated as a rough check on the measured content of 5 per cent. The analysis used is a short-cut method devised by Mouromtseff and Kozanowski*, modified in such a way as to apply to this particular case. Two simplifying assumptions are made.

The first is that the signal voltage impressed on the grids of the amplifier is sinusoidal. In the case under consideration this assumption does not hold since the grids are going quite positive on the peaks and the regulation of the drivers is not perfect.

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*See Mouromtseff and Kozanowski, a "Short-cut" Method for the Calculation of Harmonic Distortion in Wave Modulation, Proc. I.R.E., Sept., 1934, P.1090.

Therefore the system must be modified. A study of Graphs III and IV show that the voltage generated by the drivers for an output of 12.5 watts from the amplifier, has an amplitude of 93.0 volts and is sinusoidal. Then the instantaneous voltage applied to the grids of the output tubes is

$$e_g' = e_g - i_g R_D$$

where e_g is the instantaneous voltage developed by the drivers, i_g is the instantaneous grid current and R_D is the equivalent driver resistance viewed from the grids of the output tubes. The equivalent driver impedance also has a small reactive component, which is neglected in this work. R_D is readily calculated and i_g can be estimated from its average value and the angle through which it flows. For more accurate work it is necessary to know the exact wave shape of i_g.

The second assumption is that the amplifier is balanced, so that all even harmonics balance out and do not appear in the output. This assumption is seldom strictly true in practice, but may be made in this work since the tubes were found to be well matched. For calculation of harmonic distortion where unbalance exists the reader is referred to "Electric Circuit Analysis", by M. G. Malti.

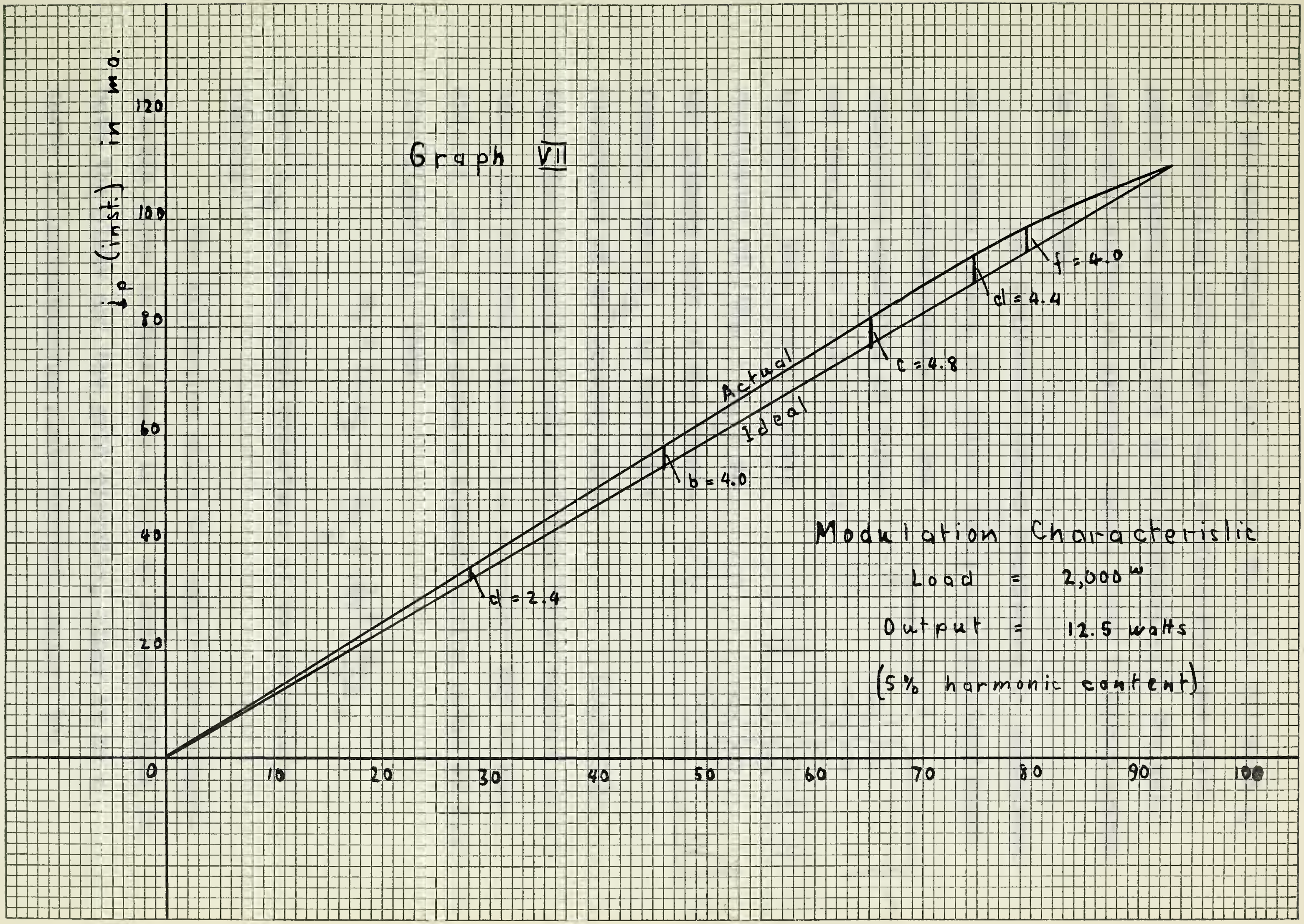
The method used is as follows. In the first column of Table I, angles over a quarter of a cycle are listed. This is all that is necessary because of the

balance assumed above. The corresponding values of e_g, the voltage developed by the drivers, are listed in the next column for a sinusoidal wave of amplitude 93.0 volts. The values of grid current, i_g, are estimated as explained above. The values of the voltage, e_g', as applied to the grids are now readily found, taking R_D = 667 ohms.

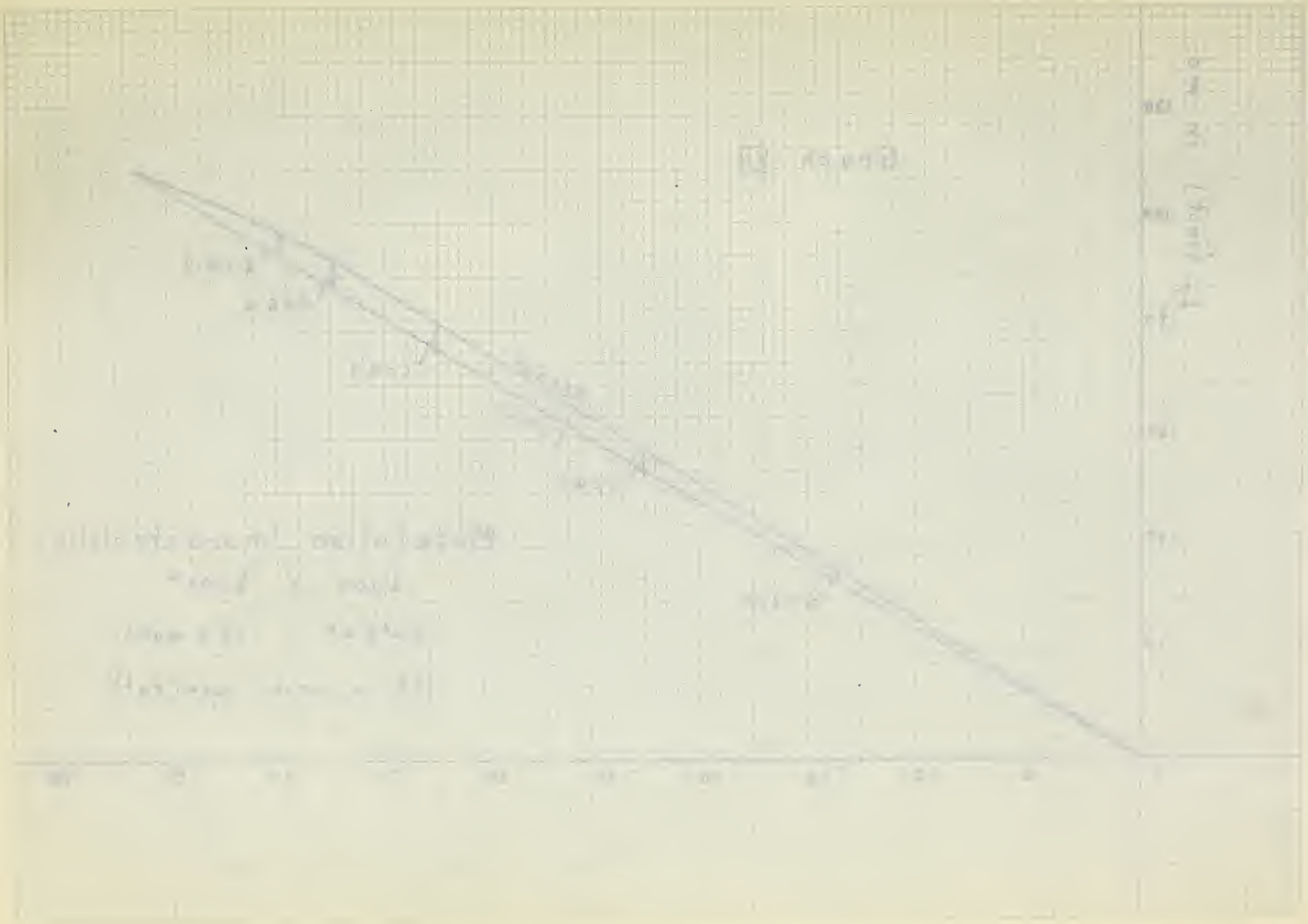
θ	e_g	i_g	$i_g R_D$	e_g'	E_g	i_p
Electrical Degrees	volts	ma.	volts	volts	Volts	ma.
0	0	0	0	0	-45.0	0
10	16.1	0	0	16.1	-28.9	19.0
20	31.8	0	0	31.8	-13.2	39.0
30	46.5	0	0	46.5	1.5	59.3
40	59.7	1	0.67	59.0	14.0	75.6
50	71.3	2.5	1.67	69.6	24.6	90.0
60	80.6	4.0	2.66	78.0	33.0	99.5
70	87.4	5.5	3.66	83.7	38.7	105.4
80	91.5	7.0	4.66	86.8	41.8	109.5
90	93.0	7.5	5.00	88.0	43.0	110.3

Table I

After finding the corresponding values of E_g, the potential of the grids relative to the cathode; the values of i_p, the plate current, are found from the characteristics of Graph VI and listed in the last column. i_p is now plotted against e_g, as in Graph VII. This curve is known as the modulation characteristic and its departure from linearity is a measure


Graph VII

Modulation Characteristic
Load = 2,000 ω
Output = 12.5 watts
(5% harmonic content)



of the distortion present. It is the line followed by the operating point over half a cycle for some given power output, and is not to be confused with the output-input curves of similar shape, shown in other Graphs in this work.

The equivalent driver resistance is calculated as follows. Since the driver tubes are operating class A, they are equivalent to two generators connected in series and their plate resistances add together. This gives a total resistance of $(2R_p + R_{T_1})$ on the primary side of the transformer, where R_{T_1} is the total resistance of the primary winding. Now the grid of only one tube draws current at a time, and the other side of the secondary may be considered open. This gives a transformation ratio of 3:1 (See figure 6). Then

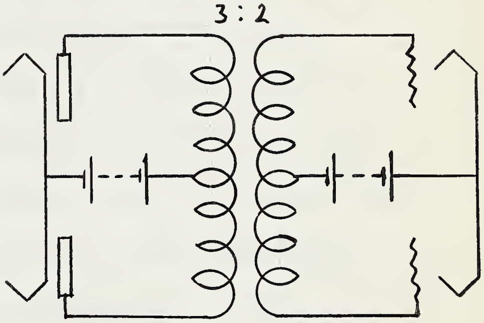


Figure 6.

$$R_D = (2\,R_p + R_{T_1})\left(\frac{1}{3}\right)^2 + \frac{R_{T_2}}{2},$$

where R_{T_2} is the total resistance of the secondary winding.

The distortion which the modulation characteristic shows in this case is due to irregularities in both the plate and the grid circuits, since it is a curve of instantaneous plate current against the

instantaneous voltage generated by the drivers. Therefore an analysis of this curve will give the total harmonic content introduced by the output stage. The harmonic content, thus calculated, by the method devised by Mouromtseff and Kozanowski is 4.80 per cent while the measured content is 4.40 per cent. The calculated value is the maximum possible since the per cent content of each harmonic is calculated separately and all are added together arithmetically. The measured value is the minimum possible since it is obtained by subtracting 0.6 per cent, the content in the oscillator output, from 5 per cent, the content in the amplifier output, as though the harmonics introduced by each are exactly in phase. The check then is close, in spite of the approximate values of grid current used in obtaining the modulation characteristic.

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DISTORTION WITH RESISTANCE IN THE PLATE SUPPLY

Many different forms of impedances are found in the plate supply of class B amplifiers; depending upon the type of supply, generator or rectifier, and the type of filter used. The problem is further complicated when the same supply serves the radio-frequency stages of the transmitter as well as the audio stages. A general solution of the problem is difficult , if not impossible. In this work an attempt was made to study the effect on distortion of resistance in the plate supply. Large values of resistance were used so that the effects of other impedances in the power supply would be relatively small.

In Graphs VIII and IX, curves of output current and corresponding curves of harmonic content, forvarious resistances added to the plate supply, are plotted on an input voltage base. The curves of Graph VIII are for a 2,000 ohm load and those of Graph IX for a 5,000 ohm load. A knowledge of the current drawn from the power supply by a class B audio amplifier is necessary, however, before the curves can be analysed.

A rough consideration of the problem might lead one to expect that this current would be closely represented by a sine wave with the negative half cycles turned up. An oscillographic record, however, showed that in this case it consisted of a large d-c component with an a-c component of twice the signal frequency impressed on

top of it. (See figure 7) This d-c component was much larger than the normal d-c component flowing when no signal was impressed. It is due to an effect known as self-rectification occuring in the vacuum tubes.

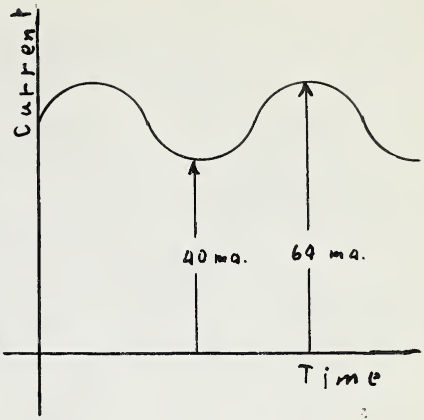

Figure 7

Preisman* states, "In the general case of a tube with curved characteristics, the plate current - when a signal voltage is impressed upon the grid - contains not only a-c components, but often a d - c component in addition to the normal d-c component". When the characteristics are concave upwards - as in the case of a triode - the former is additive and the total d-c component rises when a signal is impressed. When the load resistance is small the plate current is large, and self-rectification is in general large.

The characteristics shown in Graph II are quite curved. Thus each tube in the amplifier used in this work would be expected to draw a considerable d-c component of current, and this current would account for the large d-c component occuring in the plate supply circuit.

Preisman shows that even for normal operation, with no impedances added to the plate supply, the operating point shifts away from the quiescent

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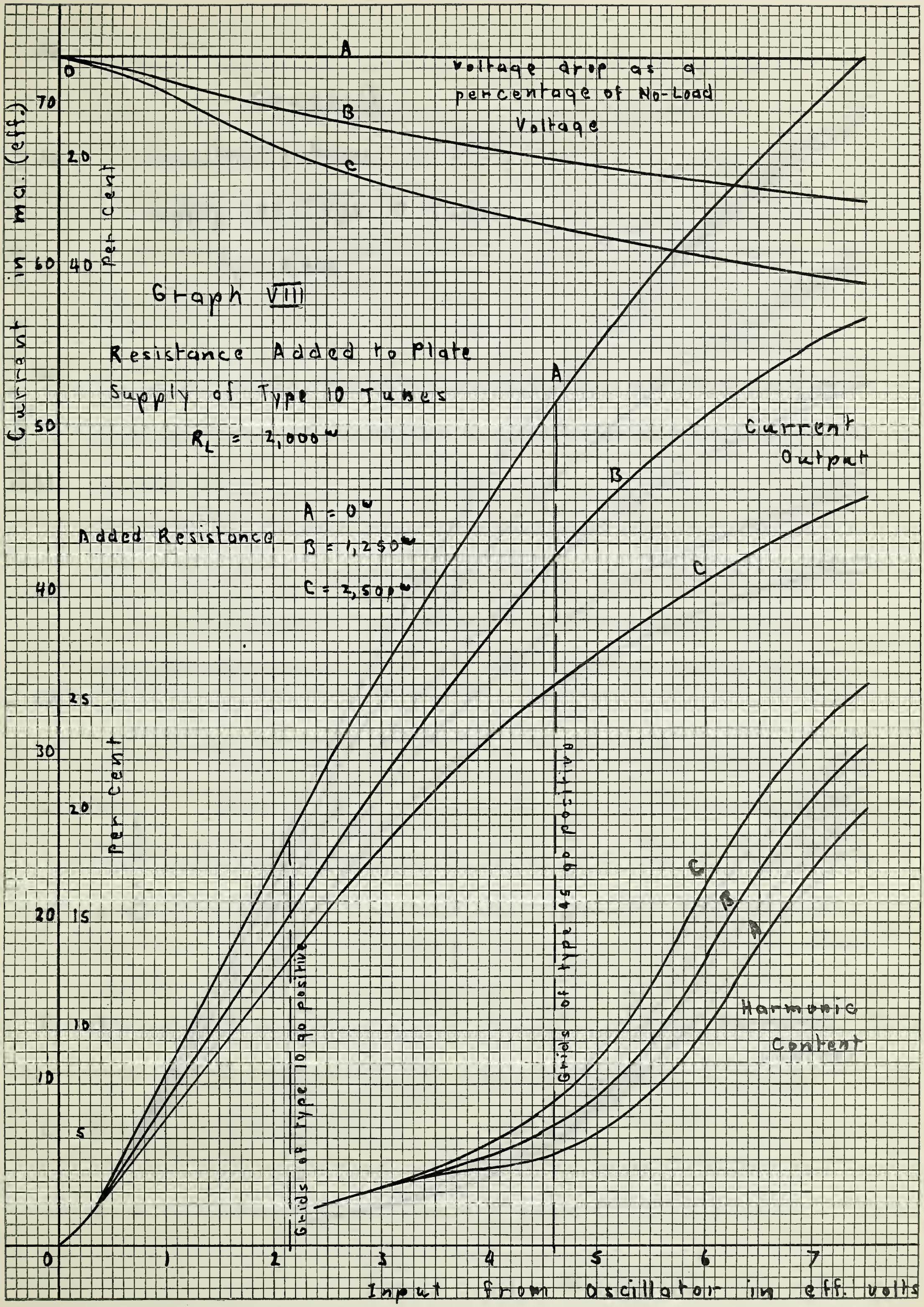
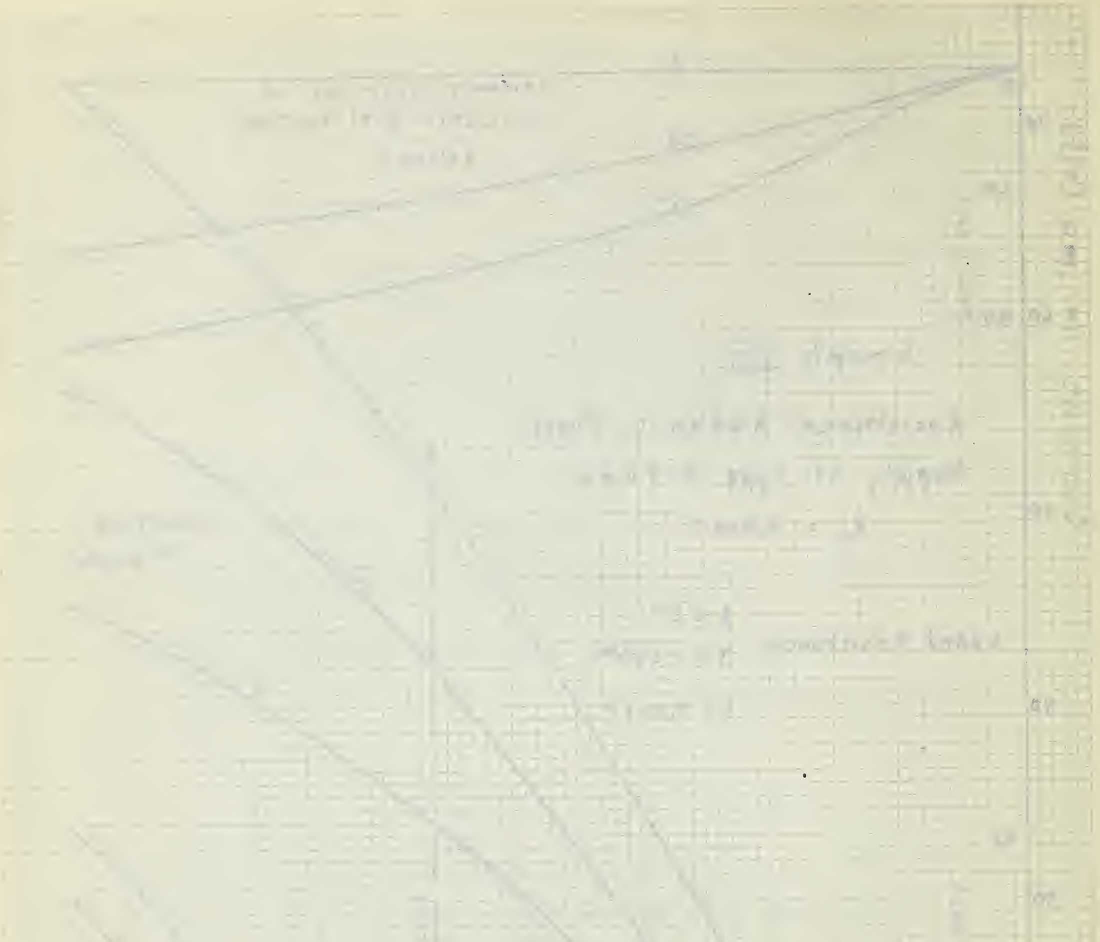
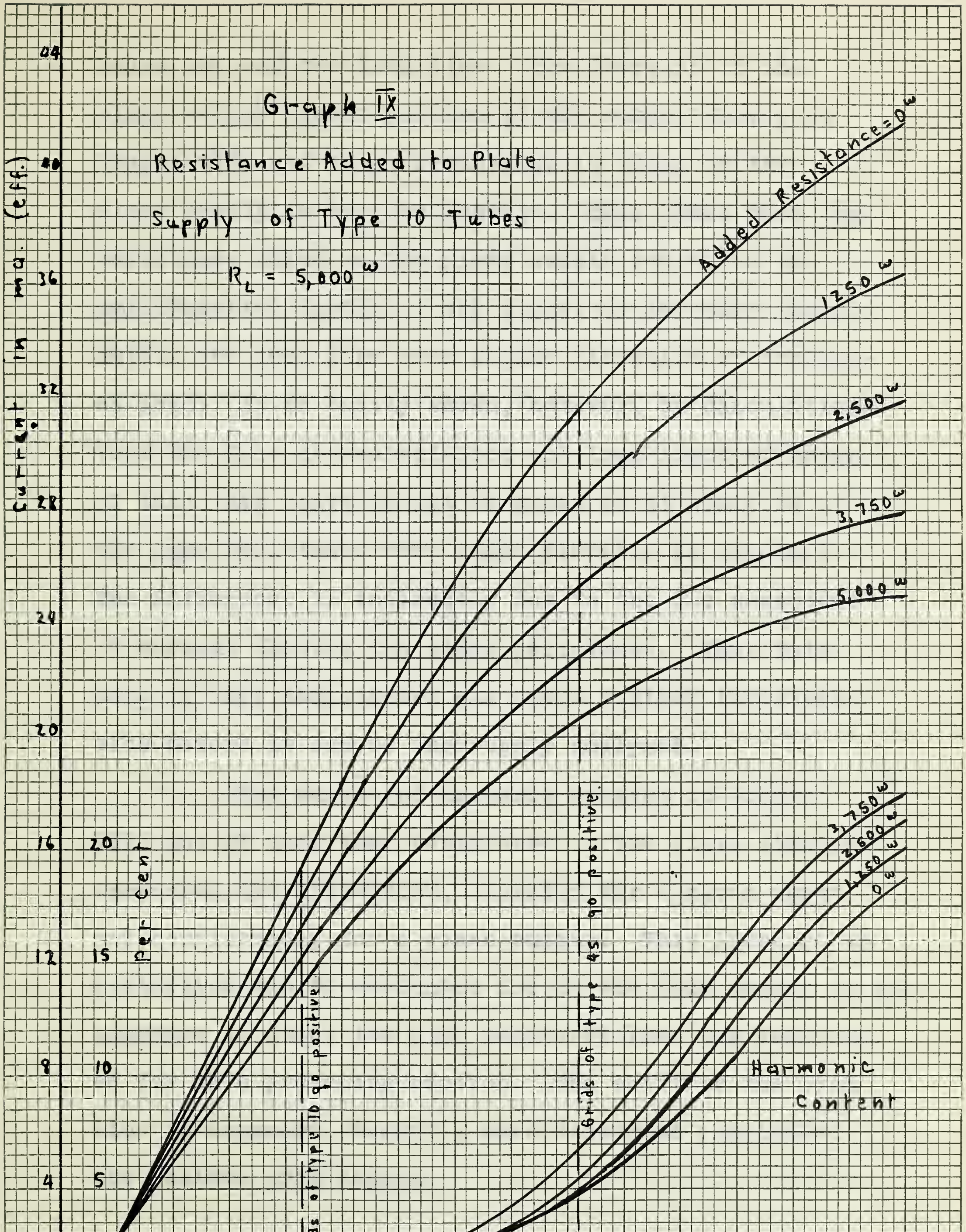
*See Albert Preisman, Balanced Amplifiers, Communication and Broadcast Engineering, February, 1936, P.15.


Graph VIII

Resistance Added to Plate Supply of Type 10 Tubes

R_L = 2,000ω


Resistance Augmenting Trim
Added Resistance
0
10
20
30



Graph IX

Resistance Added to Plate Supply of Type 10 Tubes

$R_L = 5{,}000^{\omega}$

point and off the load line. The decrease in the slope of the linear portion of the output curves of Graphs VIII and IX as resistance is added to the plate supply is very noticeable. This shows that the resistance added to the plate supply decreases the amplification factor of the stage; or in other words, shifts the load line over in the direction of increased load. It is easily shown, however, by calculations from the tube characteristics and load lines of Graph VI that this shift is not as great as it would be if the same resistance were added directly to the load. The difference is indirectly due to the d-c component of current through the added resistance. Thus this case is very complicated and needs further investigation before it can be thoroughly analysed.

The curves of harmonic content in Graphs VIII and IX show that resistance in the plate circuit increases the distortion, slightly for a given input and considerably for a given output. This increase in distortion can be accounted for in the same manner as the increase in distortion with increased load was accounted for in a preceding section. The shift in the load line is downward, toward a more distorted portion of the positive grid region.

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Another factor contributing to distortion in this case is the regulation in the power supply. The large d-c component of current referred to above, causes a d-c voltage drop through the added resistance. Thus the plate voltage changes with load, but the grid bias remains fixed; and if the grid bias is correctly adjusted for no load, the operating point will be beyond cut-off, under load. Distortion increases rapidly as the operating point is pushed into the class C region.

Curves of the drop in plate voltage under load, are plotted in Graph VIII and expressed as a percentage of no-load voltage. These curves show that an harmonic content of 5 per cent, increases to 6.5 per cent for a resistance of 1250 ohms in the plate supply, and a voltage drop on the plates of 20 per cent. Similarly, an harmonic content of 5 per cent, increases to 7.7 per cent for a resistance of 2,500 ohms in the plate supply, and a voltage drop on the plates of 32 per cent. It should be noted, however, that the increase in harmonic content for the same output is much greater. Thus, in the first case the harmonic content increases from 5 per cent to 18 per cent for the same output and a voltage drop on the plates of 40 per cent. There is also a considerable decrease in efficiency.

An important point to notice here is that relatively large resistances were required to obtain these effects. Therefore, it should be possible, in the design of a power supply, to keep distortion from this source small enough to be neglected.

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DISTORTION WITH RESISTANCE IN THE GRID CIRCUIT:

Resistance in the grid circuit is one of the most important causes of distortion in class B audio amplifiers. Fortunately, however, distortion from this source can be reduced by careful design to a point where it is negligible relative to the distortion introduced in the plate circuit by the curvature and irregularities of the plate current curve.

This distortion in the grid circuit is caused by the non-linearity of the impedance offered to the drivers by the grids of the class B amplifier. For large power outputs the class B amplifier is operated with its grids swinging decidedly positive on the signal peaks. Thus the grid of each tube goes positive over a part of the cycle, offering a relatively small impedance to the drivers; while over the remainder of the cycle the grid is negative, offering an almost infinite impedance to the drivers. As a result of this, current is drawn from the drivers on the signal peaks only; and unless the regulation of the drivers is zero, the voltage impressed on the grids will not equal the voltage developed by the drivers over the entire cycle. The peak voltage impressed on the grids is therefore less than the peak voltage developed by the drivers when the grids are swinging positive. This results in amplitude distortion and increased harmonic content in the output when the input is great enough to drive the grids positive on the peaks.

These effects were brought out in the section on the normal operation of the amplifier, when the effects of the grids of the drivers going positive were discussed. The same results are shown more clearly by the curves of Graphs X and XI. The output current and the corresponding harmonic content are plotted on an input voltage base for several different resistances added to the grid circuit of the class B stage. The curves of Graph X are for a 2,000 ohm load and those of Graph XI for a 5,000 ohm load. In both sets of curves the increase in amplitude distortion and harmonic content for increased resistance in the grid circuit is very marked. Both set in just after the amplitude of the signal becomes great enough to drive the grids of the class B amplifier positive on the peaks. The "humps" in the curves of harmonic content are clearly due to the resistance in the grid circuit, and the small hump in the curve for no added resistance is due to the resistance already in the circuit.

It was shown in the section on the calculation of harmonic content that when the drivers are operated class A this resistance is given by the formula

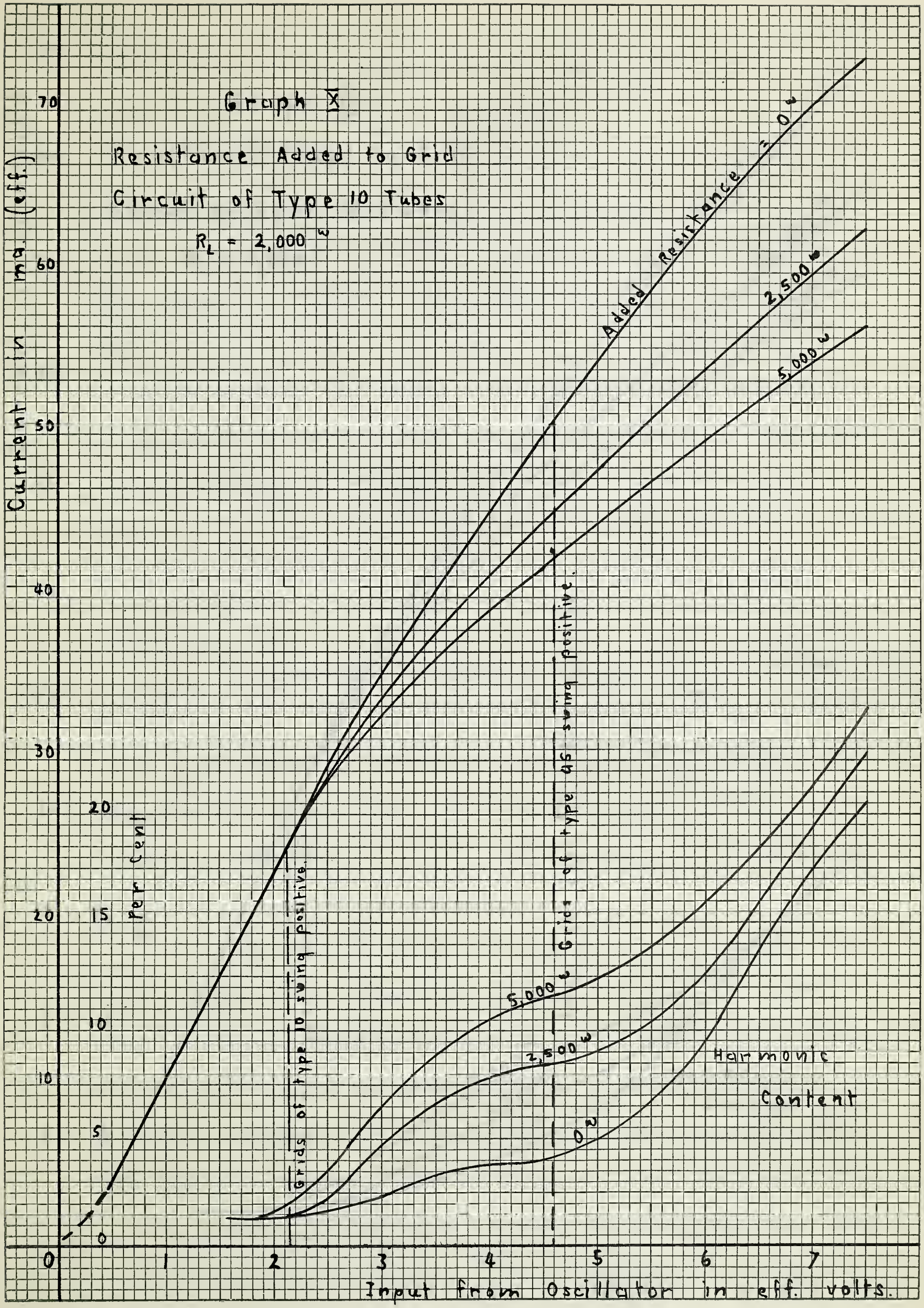
$$R_p = (2 R_p + R_{T_1}) \frac{n^2}{4} + \frac{R_{T_2}}{2}$$

where R_p is the plate resistance of a driver tube

R_{T_1} is the resistance of the total primary winding of the coupling transformer

R_{T_2} is the resistance of the total secondary winding

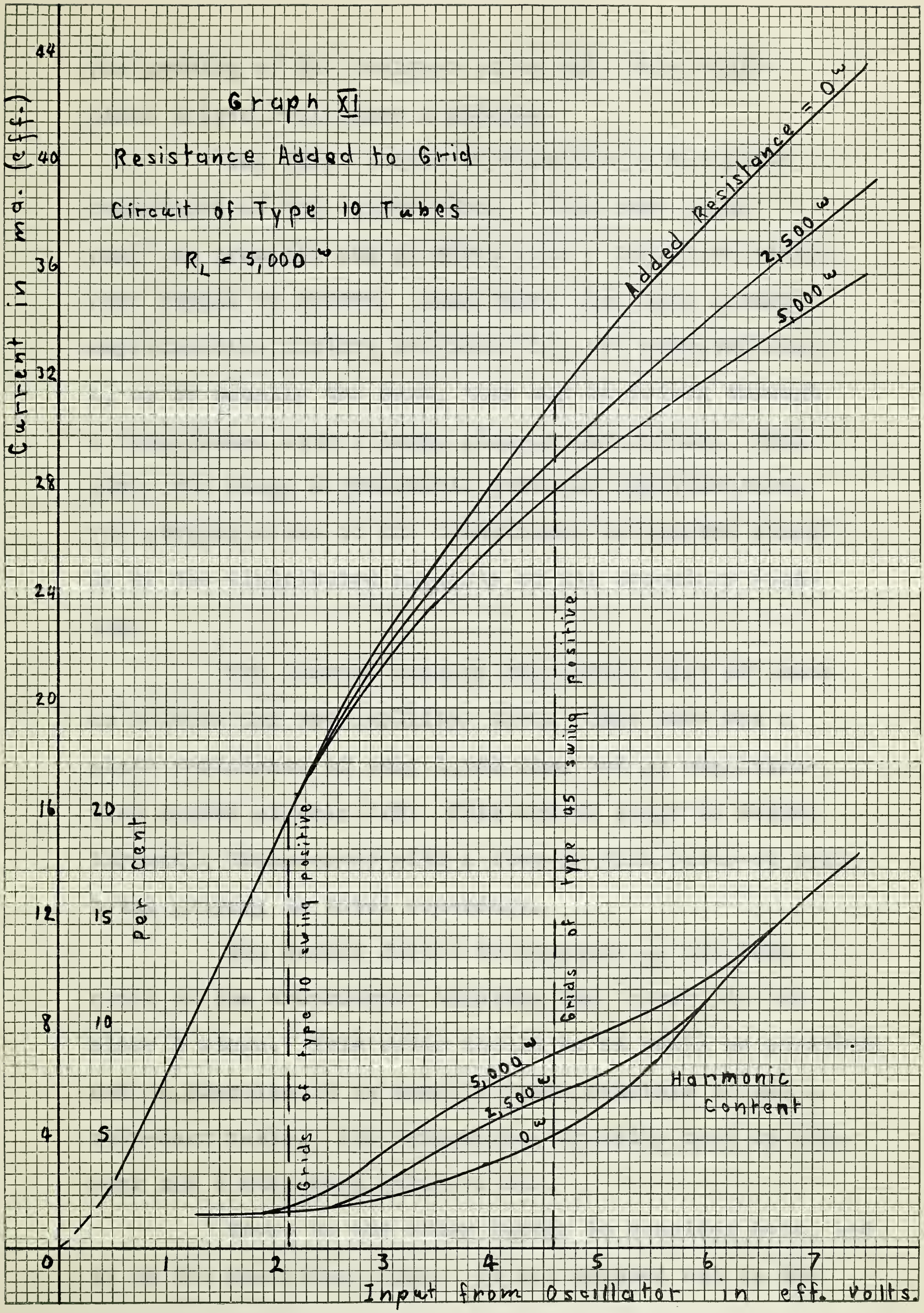
and n is the turn ratio.



Graph X

Resistance Added to Grid Circuit of Type 10 Tubes

$R_L = 2,000^{\omega}$



Graph XI

Resistance Added to Grid

Circuit of Type 10 Tubes

$R_L = 5,000^{\omega}$

The problem of the designer is to make this equivalent driver resistance a minimum.

The first factor to consider is the plate resistance of the driver tubes. This must be as small as possible and so tubes with a low plate resistance should be chosen. Such tubes also have a small amplification factor; but when they are operated class A, as is usually the case, they may be driven through a transformer with a large step-up turn ratio. This gives the stage a reasonable over-all amplification. The step-up ratio of the transformer is limited chiefly by the distributed capacity of its secondary winding.

The Hammond Company recommends type 45 tubes as drivers for the amplifier used. This tube has a plate resistance of only 1,650 ohms, but an amplification factor of only 3.5. This driver stage is driven through a transformer with a step-up turn ratio of 1:10, total primary to total secondary.

The second factor to consider is the turn ratio of the transformer coupling the drivers to the class B stage. This ratio should be as small as possible, and in practice it is usually found possible to use a step-down ratio. The transformer actually used in this work had a step-down ratio of 3:2.

There is one other factor to consider here, and it is the operating point. It was pointed out in the

section entitled Normal Operation, that the grids of the class A drivers should not go positive on the peaks. Furthermore, the step-down turn ratio of the coupling transformer demands that the class A stage develope a large voltage output. It has already beeh shown that this voltage is developed largely in the input transformer of the class A stage and the voltage swing on the grids of the drivers is therefore relatively large. This is compensated for by the fact that a tube with a small amplification factor has a low grid cut-off voltage and large swings are possible without driving the grids positive.

The resistance of the transformer windings should also be as small as possible, but the subject of transformer design cannot be treated here.

The resistance of the source of bias on the class B tubes should also be added into the equivalent driver resistance. It was neglected in this case because new batteries were used and it was relatively small. When the bias is obtained from a generator, the inductance of the armature must also be taken into consideration.

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SUMMARY

A few rules to be followed in the design and operation of class B audio-frequency amplifiers, brought out in this work, are as follows.

1. The tubes of both the amplifier and the driver stage should be operated at the highest possible plate voltage. When this is done the cut-off grid voltage has its maximum possible value and the signal that can be applied to the grid without driving it positive is a maximum.

2. The drivers of a class B audio amplifier should be operated class AB or even class B rather than class A with the grids going very far positive. Such cases are sometimes found in practice. It should be remembered, however, that the reduced voltage required by the plates of the drivers can be obtained from the plate supply of the output stage, ~~and~~ through a voltage dropping resistor, only when the drivers are operated class A.

3. Optimum load is not necessarily the best load to use on a class B audio amplifier. It is not critical and a good output can be obtained for any load that is near optimum. A load considerably less than optimum will usually give the maximum possible power output when the harmonic content cannot exceed a fixed value. This output is obtained at a considerably reduced efficiency, but this is unimportant in small transmitters.

4. Resistance in the plate supply of a class B amplifier should be small.

5. The type of tube selected for the driver stage should have a small plate resistance and the turn ratio of the coupling transformer should be step-down when possible. Other factors, such as the resistances of the transformer windings, and the impedance of the grid bias should also be as small as possible to give the drivers the smallest possible regulation.

6. The input transformer to the drivers should have a large step-up turn ratio to balance the low amplification factor of the driver tubes, selected for low plate resistance.

In conclusion, the author wishes to express his sincere thanks to Dr. H. J. MacLeod for supervising this investigation.

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APPENDIX

The Harmonic Analyser

The system of harmonic analysis used in this investigation is known as "The Resistance Bridge Method". It is described by F. E. Terman, in his book "Measurements in Radio Engineering". A diagram of the bridge is shown in figure 8.

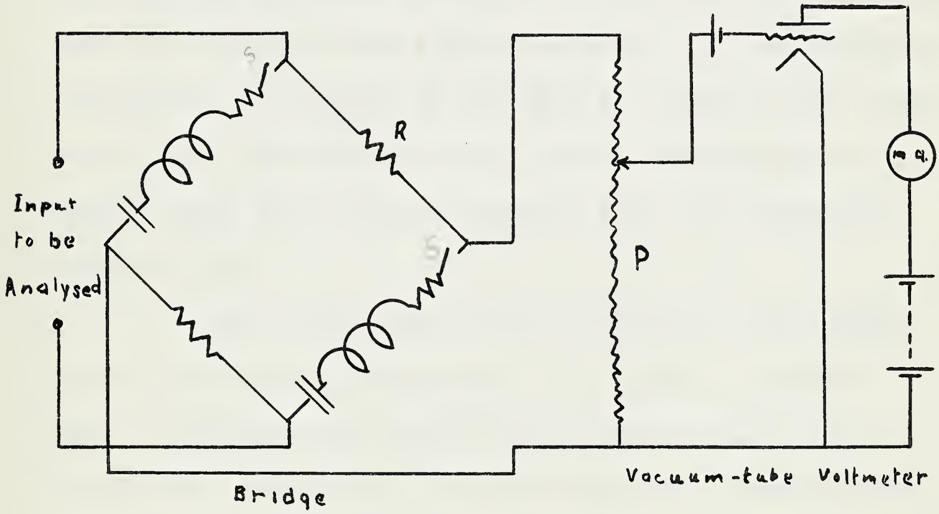


Figure 8

Each arm of the bridge contains a total predetermined resistance R. Two opposing arms also contain an inductance and a capacity tuned to the fundamental frequency of the wave to be analysed. Thus each arm offers a pure resistance impedance R to the fundamental component of current, while the arms containing inductance and capacity offer a very large impedance to the harmonics. The potentiometer P is a pure resistance and is usually taken equal to R.

When the switches S are open, all components of current are forced through P. The potentiometer is set to give a convenient reading on the milliammeter in the plate circuit of the vacuum-tube voltmeter. When the switches S are closed the bridge is balanced to the fundamental frequency and only the harmonic components of current flow through P. The potentiometer is set to give the same reading as before on the milliammeter. Then the ratio of the r.m.s. value of all the harmonic components of current to the r.m.s. value of the total current is the inverse ratio of the potentiometer settings. Thus this bridge measures the total harmonic content only.

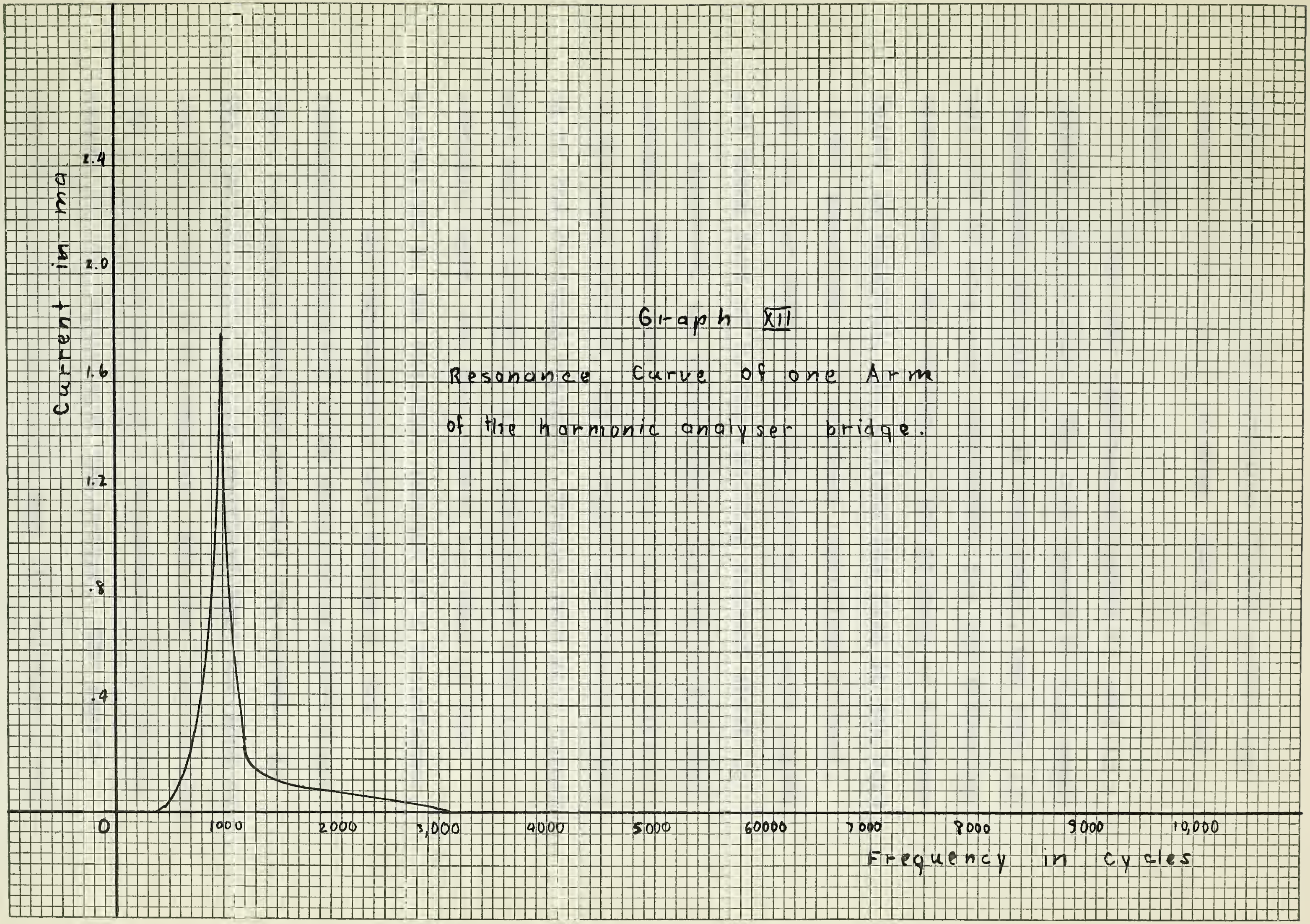
The first step in the design of the bridge is to determine P, which has to be large enough to give a voltage that can be read conveniently on the vacuum-tube voltmeter, when the smallest harmonic content to be handled is passing through it. Now the ordinary vacuum-tube voltmeter will not measure less than about 2 volts accurately, since the tube is operated at cut-off to obtain anode rectification. Conditions can be improved some, by using heater type tubes which cut-off more sharply. With this bridge, however, it is possible to place a stage of amplification ahead of the voltmeter since no calibration is necessary.

In this case it was found possible to do away with the voltmeter entirely, since the amounts

of power being analysed were relatively large. A multi-range milliammeter, reading down to one tenth of a milliampere, was simply placed in series with P. The total output current was then read directly on a high range and the total harmonic content on a low range. This method was found to be much less tedious than the other.

The resistances R and P were arbitrarily set at 1000 ohms each. Terman states that $\frac{\omega L}{R}$ should be at least 10. Thus the inductance was set at about 4 henry making $\frac{\omega L}{R}$ equal to 25 at 1000 cycles. The capacity required to resonate at 1000 cycles with an inductance of 4 henry is about .006 μf, and it was obtained with a variable condenser which made tuning possible.

The inductances used were of the non-magnetic type, and were wound with #30 enamel wire. They were designed to give a fixed inductance for a minimum length of wire, according to the rules in "Radio Engineering", by F. E. Terman, Appendix A. This reduced the effect of distributed capacity to a minimum. A variable resistance was added in series with each coil to bring the total resistance up to the required 1000 ohms. A resonance curve of one arm of the bridge is shown in Graph XII. It is a curve of the current passed by the arm for a fixed voltage across it, taken from 500 cycles to 10,000 cycles. At the fundamental frequency of 1000 cycles the response is excellent,



Graph XII

Resonance Curve of one Arm of the harmonic analyser bridge.

while at all the odd harmonics of 1000 cycles the response is too small to show. This is what was required.

Iron core inductances cannot be used in a circuit such as this. The iron losses in high grade transformers are said to be negligible, but this is not true of iron core inductances for the following reason. When the voltage on the primary of a transformer is constant, the alternating flux in the core of the transformer is constant regardless of load, and the iron losses are thus constant. These losses are taken care of by the exciting current which is also constant, and quite small relative to the load current. Thus losses which are negligible referred to the load current, may be quite appreciable referred to the exciting current. Now an iron core inductance may be thought of as a transformer with its secondary open, and the current it draws is thus equivalent to the exciting current of a transformer.

The impedance of this bridge to the fundamental frequency is 3R when the switches S are open, but only R when the switches are closed. In this investigation it was important that the load on the amplifier be held constant. This was done by placing a resistance 2R, with a short-circuiting switch across it, in series with the bridge. The short-circuiting switch was opened when the switches S were

closed, and closed when the switches S were opened. This corrected the circuit for the fundamental frequency, but not for the harmonic frequencies. Thus the load on the amplifier was held constant, but the readings of harmonic content had to be corrected by a simple multiplier.

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